NEHRU
BAL PUSTAKALAYA

A JOURNEY THROUGH THE UNIVERSE

JAYANT NARLIKAR

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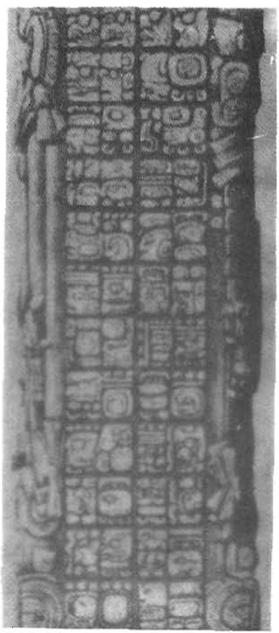

Ancient Hindu concepts of the Universe are depicted → here. It shows the Earth as resting on elephants resting on a turtle which, in turn, rests on a cobra.

← The 'Maya Stele', showing dates carved on stone. The Mayan civilization used the 365-day calendar based on the Sun.

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JAYANT NARLIKAR

Cartoons
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The concept of the Universe based on the idea of the Greek philosopher Thales (640-550 B C), in which the Earth floats like a ship on water. The central figure is Archimedes.

A JOURNEY THROUGH THE UNIVERSE

Astronomy Through the Ages

The star-studded sky on a clear night is a spectacular sight. It has inspired poets and artists to great heights of creativity. Over the ages, philosophers and religious leaders have spent their lives contemplating the starry heavens and wondering about man's place in the vast universe.

But the most common feeling that the sight inspires is one of curiosity. What are these twinkling points of light that we call stars? Are they all alike? How far away are they from us? Why do they shine? What is the status of the most spectacular of heavenly bodies, the Sun and the Moon?... And, if you are extra curious you may also wonder whether or not there are other objects out there which we cannot see with our eyes.

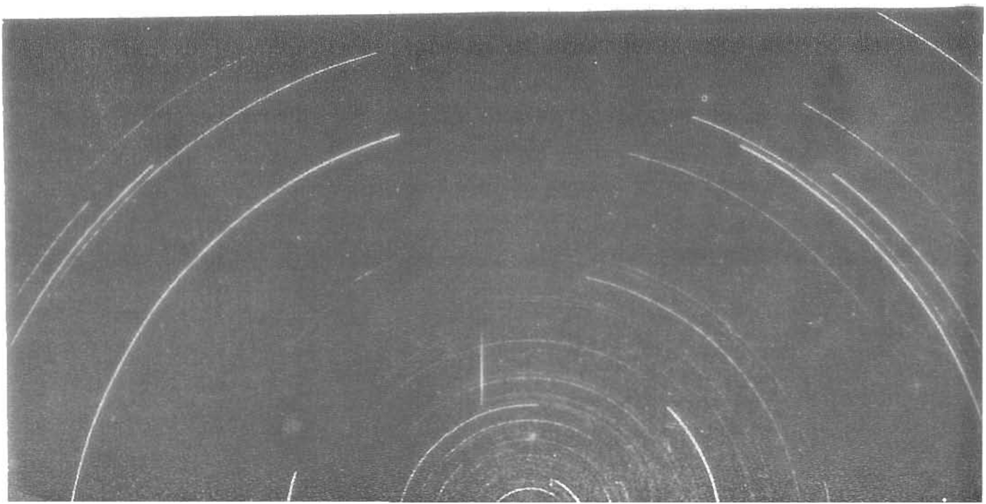
The science of astronomy was born out of this curiosity. And it can well claim to be the oldest of sciences. For, right from the earliest times, man has puzzled over these questions and tried to work out logical answers to them.

We find evidence of such attempts from the archaeological remains of ancient civilizations such as those of Egypt, Babylon, China and India. Manuscripts which have come down from the ancient Greek civilization of more than two thousand years ago, show how man tried to work out the pattern behind the somewhat chaotic movements of a handful of heavenly bodies called the planets.

What is so special about planets? You can find out for yourself if you watch the night sky for several months. First, you will see that stars, as a rule, rise in the east and set in the west, as the Sun does. There is one star, however, which does not seem to move at all. This is the Pole Star that lies towards the north. Now imagine that the night sky is a gigantic sphere with ourselves at its centre, a sphere that rotates from east to west around a line joining our position to the Pole Star. If all the stars were stuck onto this sphere, they would appear to go round this line, from east to west.

This is the picture the Greeks had constructed in describing stars. The planets, however, did not fit into the scheme so well. Instead of being 'stuck to' this revolving celestial sphere, they seemed to have additional motions of their own. This is what you

If we expose a film to a clear sky throughout the night the star-trajectories appear as circular arcs; the smallest one in the picture shows that even the Pole Star is not fixed. It is slightly off the Earth's rotation axis.



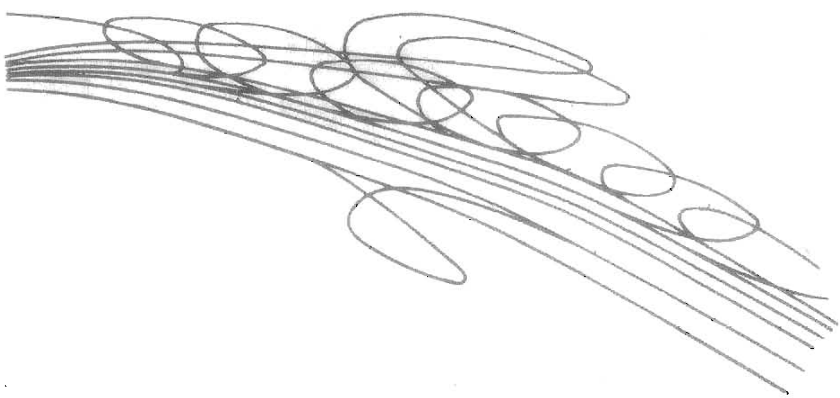
will find if, for example, you look at the positions of the planets Venus and Mars in relation to other stars. These planets appear to change their positions, and in no fixed pattern. This explains the name 'planet' which means 'wanderer' in Greek.

Why do planets wander? When confronted with this question human beings found two very different answers: one based on science, the other on superstition.

The superstitious believed that planets wander because they have some 'extra power' which is denied to stars: and out of this belief arose 'astrology'. Astrology assumes that planets are 'powerful' and exert their influence on human destiny.

But those with a scientific bent of mind tried to understand why planets move in this way. The answer was not easy or quick. About two thousand years ago the Greek astronomers, Hipparchus and Ptolemy, demonstrated that there is a pattern in the movement of planets. This pattern, however, appeared complicated because the Greeks had a stubborn belief that the Earth is fixed in space and that everything goes round it. In the sixteenth century Nicolaus Copernicus showed that the pattern of this planetary movement looked much simpler if planets (including our Earth) are assumed

The planetary trajectories appear haphazard when seen against the backdrop of distant stars. The loops in the picture indicate the observed forward and retrograde motions of planets.



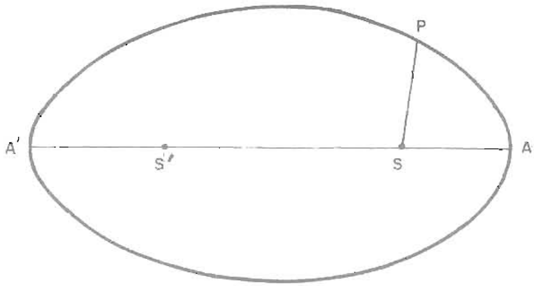
to move around a fixed Sun. But his ideas were greeted with hostility.

Earlier, in the fifth century, the Indian astronomer, Aryabhata had stated that the Earth is not fixed, but revolves around a north-south axis and this was why stars appeared to rise and set. But so great was the Greek influence in scientific matters even in India that Aryabhata's correct reasoning did not receive support even from his disciples and successors.

It was only in the seventeenth century, thanks to the researches of Galileo, Kepler and Newton, that it was well established that planets move round the Sun. By 1687 with Newton's laws of motion and gravitation the movements of planets were explained accurately and today the astronomer can predict where a certain planet will be found at any given time in the future.

As in the case of the movement of planets man's surveys of the universe over the centuries have revealed many strange

Nicolaus Copernicus.



Johannes Kepler established that a typical planet (P) moves in an elliptical orbit with the Sun (S) at one of the two foci of the ellipse. (S′ is the other focus) Kepler's laws tell *how* the planet moves on this track. Later Isaac Newton's law of gravitation, explained *why* the planets move in this way.

phenomena. To understand these mysteries, man's best tool has been science. Indeed, our many questions about the heavens have received reasonably satisfactory answers from the laws of science known to us today.

Let us begin our exploration of the universe, armed with the tools provided by science. But first let us look at these tools.

Astronomical Telescopes

Although the telescope was invented by Hans Lippershey in Holland, it was Galileo in Italy who was the first to put it to use for astronomical observations. Basically, a telescope makes use of curved reflecting surfaces and/or lenses to bend the light rays from a distant source in such a way that its clear and magnified image is formed closer to the observer. Even the human eye forms images on the retina by the same optical principles; but it has limitations regarding how clearly it can see and how faint an object it can detect.

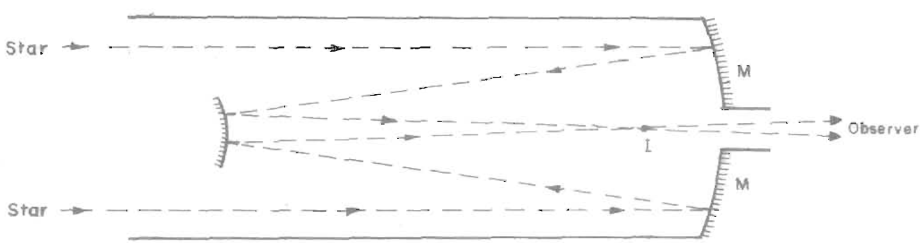
When you look at a tree in the distance you cannot make out its individual leaves. A telescope 'brings the tree closer' and enables you to see the leaves clearly. The telescope therefore increases the clarity of the object under study. In astronomical jargon we say that the telescope has improved the 'resolution'.

In the same way a large telescope can collect and focus light more effectively and therefore help us to see things that the human eye cannot see. Thus, by exposing a photographic plate to the light coming through a telescope for several hours, the astronomer is able to get photographs of faint nebulae which are otherwise invisible to the human eye.

Galileo was able to discover the four nearest satellites of the planet Jupiter by studying the planet through his newly acquired telescope. He also discovered sunspots—the dark patches on the bright disc of the Sun—that are not visible to the naked eye.

Today's telescopes are far bigger and vastly superior to the one Galileo used. The largest telescope using visible light is in Russia, although the largest working telescope is the Hale Telescope at Mount Palomar in southern California in the USA.

The diagram illustrates how a reflecting telescope works. The dotted lines are rays of light from a distant star which are reflected by the large concave mirror M and then brought into focus to form a bright and clear image at I.



This illustration of the galaxy was obtained by exposing the photographic plate for several hours. The galaxy is not visible to the human eye.

This telescope has a main mirror with a diameter of five metres. It is now planned to make even larger 'next generation' telescopes.

Technical problems make the building of very large telescopes difficult. Extreme precision is needed in the entire system if the astronomer is to trust the image that is formed by the telescope. (Have you seen your image in a mirror with an uneven surface?) To get this kind of precision the mirror has to be ground very carefully and very fine. Moreover, if the mirror 'dish' is very large it tends to sag under its own weight. The mirror also gets distorted by

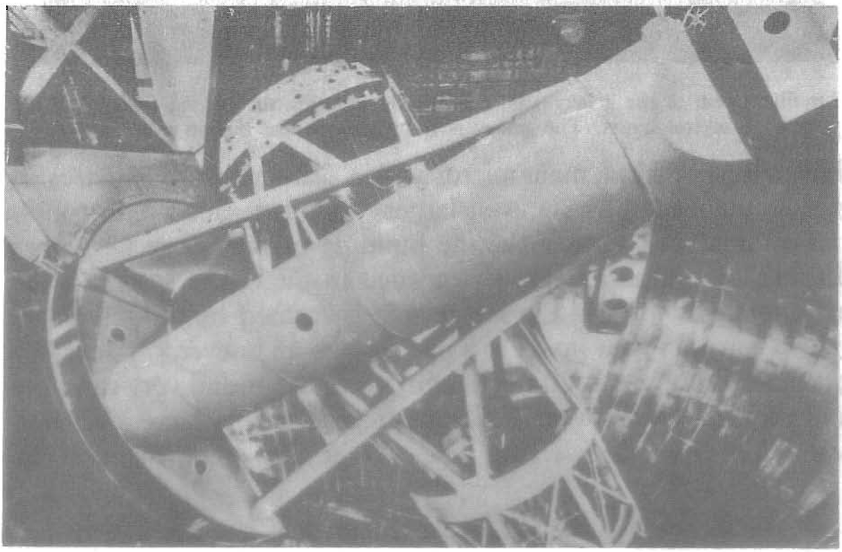
temperature changes during night and day. These effects are small for small size mirrors. So, nowadays many astronomers prefer building smaller mirrors which are linked together.

The multi-mirror telescope (MMT) at Mount Hopkins in Arizona, USA, is the first telescope of this kind. It uses high precision electronics to combine the six images formed by its six component mirrors into an even clearer and brighter single image.

The light collected by the MMT's six mirrors is therefore equal to the light collected by an ordinary telescope with a single mirror of about 4.5 metre diameter. We can call it the effective diameter of the telescope. The next generation telescopes will have effective diameters from 8-16 metres.

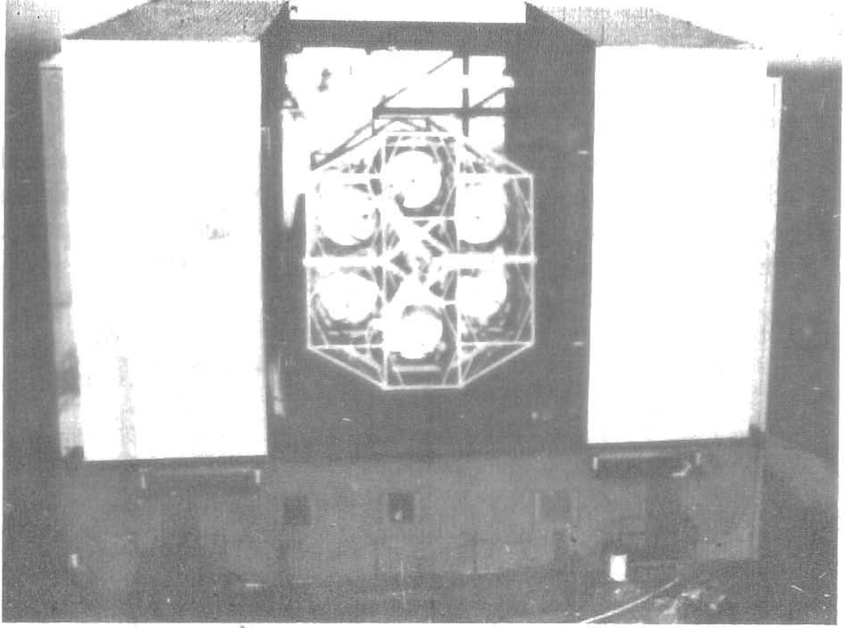
Indeed, whatever model is chosen for a future telescope, electronic devices will play a dominant role in processing the

The Hale Telescope at Mt. Palomar, California.



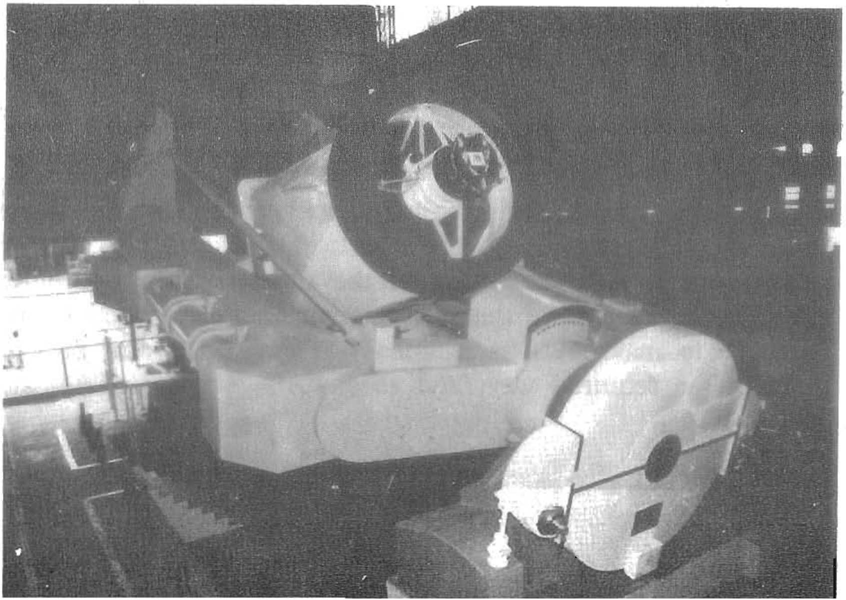
information that is brought by the light from an astronomical object through the telescope. That is why the new 2.3 metre Vainu Bappu Telescope at Kavalur in south India houses an electronic computer as an indispensable astronomical accessory.

How can a computer help the astronomer? It can help him guide the telescope accurately in the direction of the distant star or galaxy; it can form an image of the object on the computer terminal; it can control the various instruments attached to the telescope to make various technical measurements and present them in the required way, and so on.

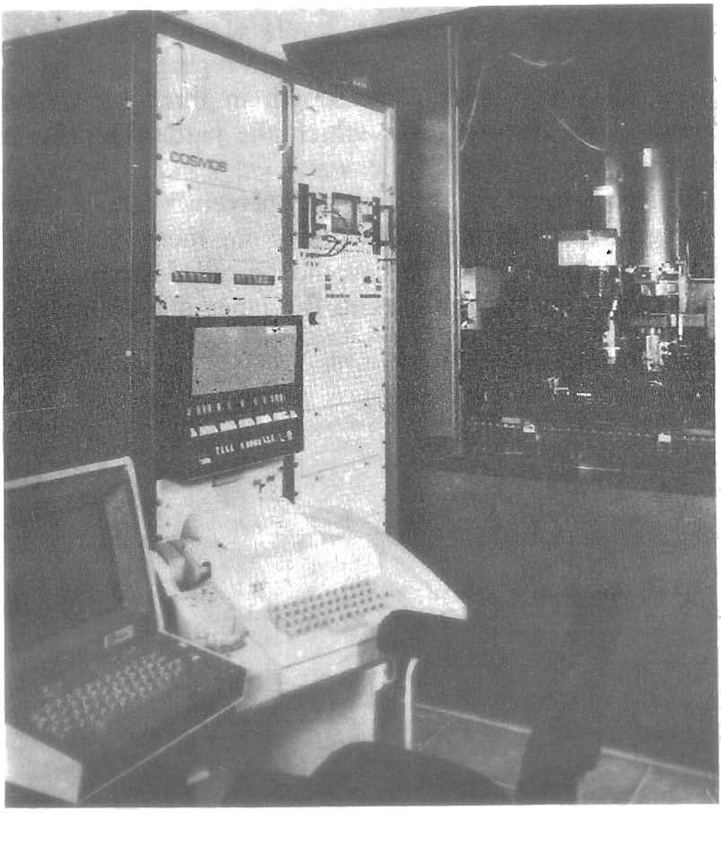


The multi-mirror telescope at Mt. Hopkins, Arizona.

The new telescope at Kavalur, south India.



Today's astronomer, however, does not confine himself to telescopes using visible light. Modern technology has provided him with other resources also.



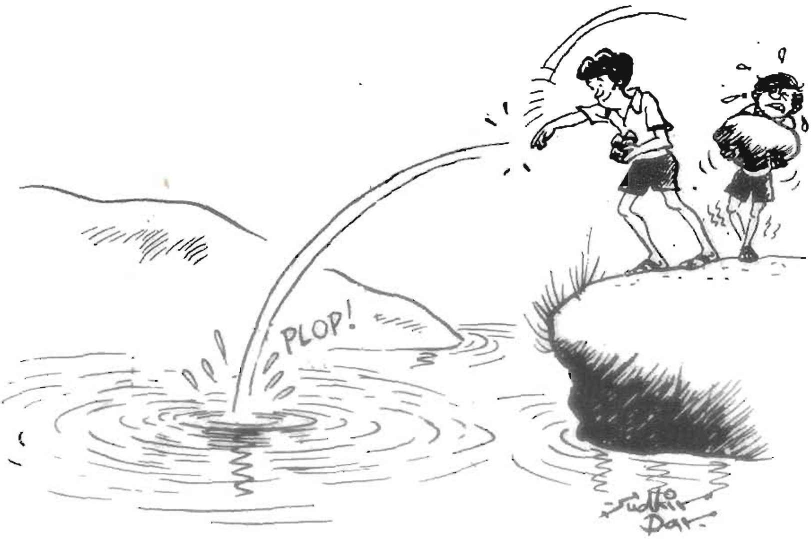
Astronomical images can be formed on the screens of computer terminals linked to the telescope. COSMOS is one such computer facility.

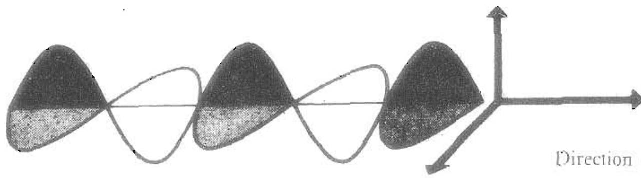
Radioastronomy

More than a hundred years ago the Scottish physicist James Clerk Maxwell established an important fact—that light is an electromagnetic wave.

Just as a pebble when dropped into a pond produces waves on the water surface, so too is light produced by a source—a wave which shows rapidly changing levels of electric and magnetic disturbances. And, just as a wave pattern repeats itself, so do these disturbances—they go up and down in intensity with perfect regularity. The distance over which the pattern repeats itself is called the 'wavelength' of the wave.

The light which the human eye perceives has a very short wavelength. If we divide the length of one metre into a thousand million equal parts, each part would be called a nanometre. The wavelength of visible light lies in the range 400-800 nanometres.





A schematic picture of an electromagnetic wave. The waves denote the undulating strengths of the electric and magnetic disturbances.

The different colours of the rainbow—violet, indigo, blue, green, yellow, orange and red have light waves of different wavelengths but within the range of 400-800 nanometres. Red has the longest wavelength and violet, the shortest. Telescopes using visible light are called 'optical' telescopes.

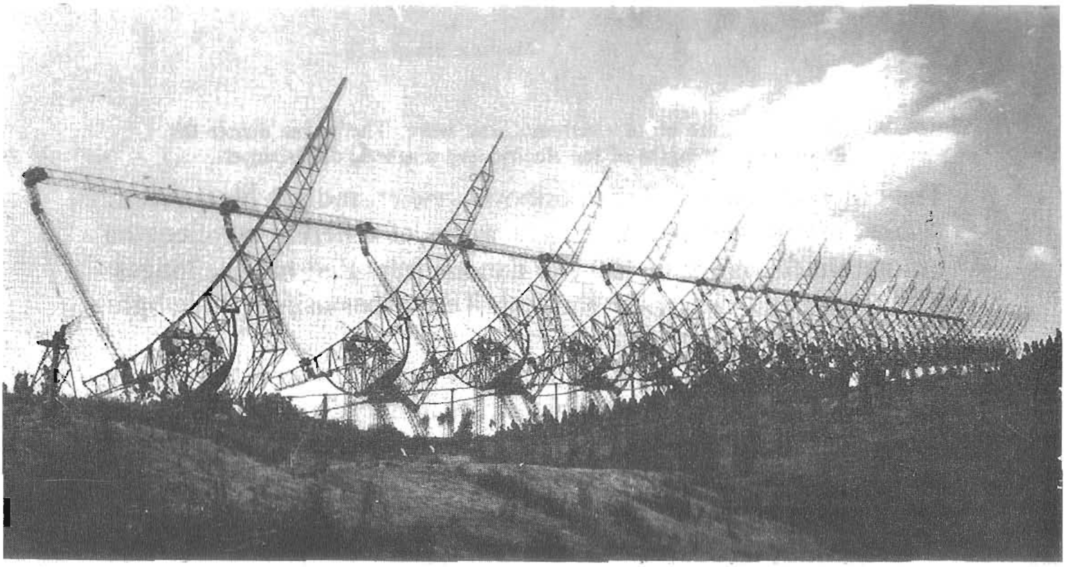
But, the important aspect of Maxwell's findings for astronomy is contained in the question: "What sort of light is described by waves whose wavelengths do *not* fall in the 400-800 nm band?" For, if such light exists, our eyes do not respond to it. Can we, however, detect its existence in some other way?

The answer is "yes". We do it everyday—for example, when we switch on the radio. Radio programmes are transmitted over 'radio waves' that have much longer wavelengths than the waves of visible light. When you listen to a medium-wave programme on 25 metres, this programme is brought to you by electromagnetic waves of 25 metres wavelength.

The first scientist to appreciate the importance of radio waves for astronomy was Karl Jansky in the 1930s. Just as optical telescopes help us obtain important information about sources of visible light

in the universe, radiotelescopes tell us about the emitters of radio waves in the universe.

Although it is barely fifty years since Jansky made the first radio detector, technology has advanced so rapidly that now huge radio telescopes are found all over the world. The big radio telescope at



The array of antennae that constitute the Ooty telescope.

Ootacamund in south India is more than half a kilometre long. The world's largest radio telescope at metre wavelengths is being built at Narayangaon near Pune. It will have 30 dishes of 45 metre diameter spread over an area of several square kilometres. Radioastronomers have not only built large individual telescopes, but they have also linked them across continents so as to improve

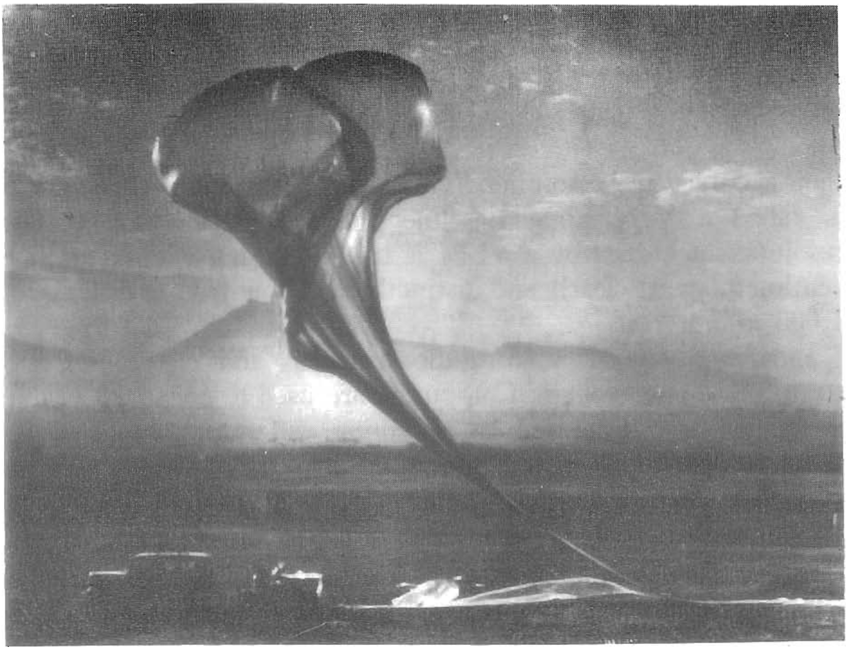
their accuracy and resolution. This kind of linked telescope system is called a Very Long Baseline Interferometer (VLBI). The resolution achieved by a VLBI is like observing two points one centimetre apart clearly and distinctly made out from a distance of 1,000 kilometres!

In the development of radioastronomy too electronics has contributed enormously. Computers are used to construct visible images of a radiosource by ascribing different colours to its different parts according to their brightness—much like a geography map in which mountain ranges of different heights are shown by different colours. This is called 'image processing'.

Space-astronomy

Besides radio waves and visible light waves there are other types of waves with varying wavelengths such as microwaves, infrared, ultraviolet, X-rays and gamma rays. Do we have telescopes for them too? We do; but not on the surface of the Earth. For, the Earth is surrounded by a gaseous layer of atmosphere that absorbs these waves coming from outer space. If we want to detect these waves, we have to set up our detectors above the atmosphere.

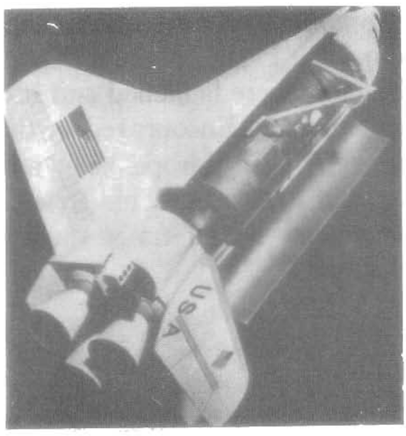
Space technology enables us to do this. At a modest level detectors are sent up in balloons and rockets but at a more ambitious level, detectors can be placed in a satellite that goes round the Earth. In the 1970s and 1980s many satellites with such detectors were launched and brought back new information about our universe. Encouraged by these successes the space agencies of the USA and Europe have now joined hands in sending forth a *space telescope*. This telescope mainly uses visible light, but it can be 10 times more efficient than the ground based telescopes.



Balloon launching at Hyderabad.

The detector on the X-ray satellite UHURU launched in 1972.

The space telescope launched in 1990.



Thus, man's advances in technology continue to help him in his search for the answer to the ultimate question: "What is our Universe like?"

Let us now turn our attention to the answer provided by our present-day tools.

What is the Universe like?

We start our journey from the Earth.

Of course, to the inhabitants of the planet Earth the most spectacular object in the sky is the Sun. About 150 million kilometres from us, the Sun controls the movements of not only the Earth but eight other planets as well. Two of these planets are nearer the Sun than the Earth and the other six lie further away. Astronomers have a special unit called the 'astronomical unit' to measure distances within the solar system. One astronomical unit (AU) equals the distance between the Sun and the Earth. The outermost planet of the solar system, Pluto is about 39 AU away from the Sun.

The AU is a good unit of measurement within the solar system, but it is too small for distances to stars. (It would be like using centimetres to measure the distance between Bombay and Delhi!) We, therefore, use the 'light year'. One light year (L.Y.) is the distance travelled by light in one year. Now, you know that light travels at a speed of about 3,00,000 kilometres per second. In a year there are nearly 30 million seconds. So light travels a distance of nearly 10 million million kilometres in one year. Enormous though this figure seems, we will find that even the light year is too small a unit to measure the size of the Universe. But let us continue our journey in stages.

Not all the stars seen in the sky are at the same distance from us,

TABLE
Some facts about planets around the Sun

Planet	*Radius (in kilo-metres)*	*Mass (Compared to the Earth's mass*)*	*Length of the day (in Earth-days)*	*Length of the year (in Earth years)*	*Distance from the Sun in AU**	*Number of moons*
Mercury	2,439	0.056	58.7	0.24	0.39	—
Venus	6,050	0.81	243	0.61	0.72	—
Earth	6,378	1.00	1	1	1	1
Mars	3,394	0.11	1	1.88	1.52	2
Jupiter	71,880	318	0.4	11.86	5.20	16
Saturn	60,400	95	0.43	29.46	9.55	17
Uranus	23,540	15	0:43	84.01	19.2	5
Neptune	24,600	17	0.62	164.79	30.1	2
Pluto	1500	0.002	6.4	248.4	39.5	2

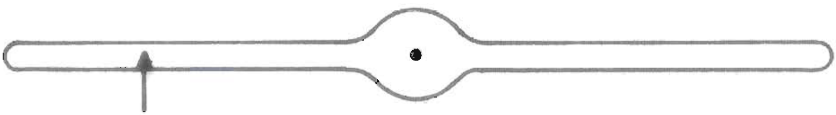
* AU = Astronomical Unit = 1.496 million kilometres
Earth mass =6 million million million million kilogrammes

as the ancient Greeks believed. The nearest star Proxima Centauri, is about $4^1/_4$ light years away from us. So when you glimpse this star you see it as it was $4^1/_4$ years ago. And, of course, other stars are even further away.

How far do we have to travel to get to the furthest star that we see? Let us look at this question somewhat differently. First we have to realize that the Sun itself is a star. It looks so bright to us because we are so close to it. A 60-watt bulb appears bright in your room at night, but the same bulb seen from far away appears to be a mere point of light. In the same way, stars appear faint compared to the Sun, not because their light is less powerful but because they are so far away. Indeed, there are stars which are so faint that we cannot see them with our eyes but can only see their images on photographic plates taken through a telescope.

Astronomers have now found out that the solar system and all the stars we see are part of a gigantic group called the Galaxy. The Galaxy looks like a flattened bun with a small bulge at the centre. Its diameter is 100,000 L.Y. and the entire system has more than one hundred billion stars (1 billion=1,000 million). Since the Earth is a part of the system, we see those stars that are more densely concentrated in a band going round us. This white band is called the Milky Way.

Astronomical photographs of the Milky Way and other parts of the sky do not, however, show a continuous white band. There are dark patches within the white band. For a long time astronomers



Schematic picture of our Galaxy. We are located at the arrow about two-thirds of the way distant from the centre of the Galaxy.

Montage of the Milky Way made up from photographs taken in different directions.

thought that the dark patches were due to an absence of stars. This impression was wrong. These dark patches are caused by pollution of the Galaxy! Apart from stars, the Galaxy contains a small amount of gas and dust and these tend to absorb starlight and lessen the range of one's vision. Just as thick fog, or industrial smog, cuts down visibility, dust between the stars curtails what the earthbound astronomer can see.

How much of a star's light is absorbed en route to us depends on the absorbing material and the wavelength of the light. Light of short wavelengths (blue and violet colours) tends to be absorbed and scattered more than light of long wavelengths (red in colour). This is why light from a source gets progressively reddened as it moves away from the source and the nature of reddening can tell the astronomer what kind of dust is responsible for it.

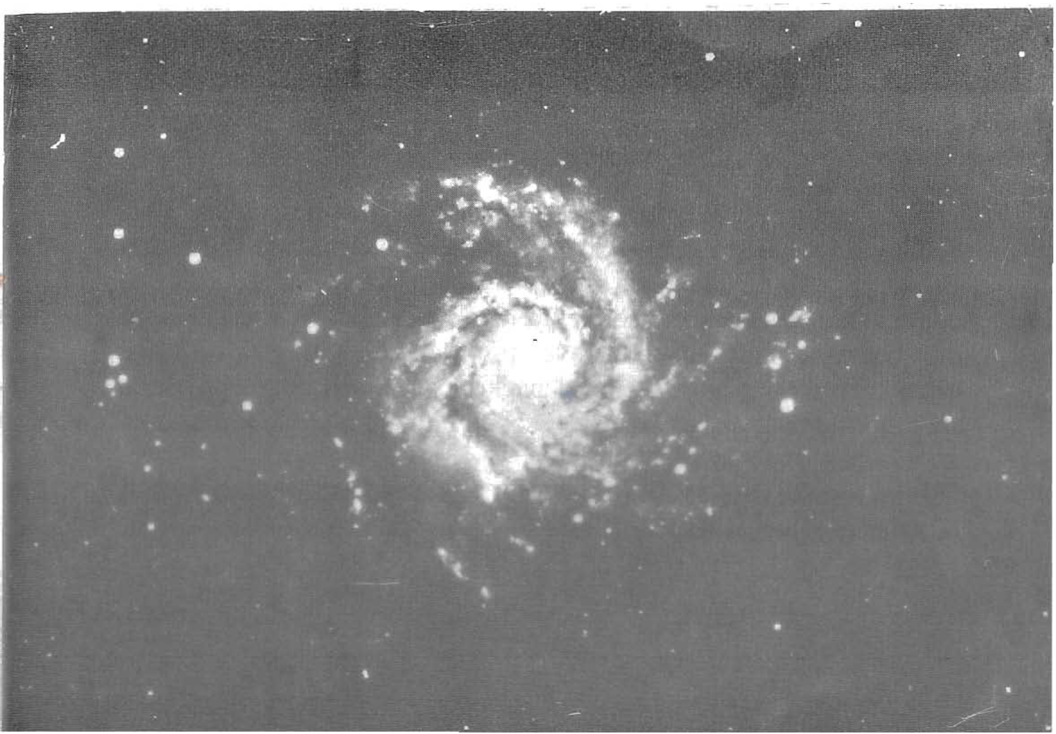
The telescopes of the twentieth century also proved wrong

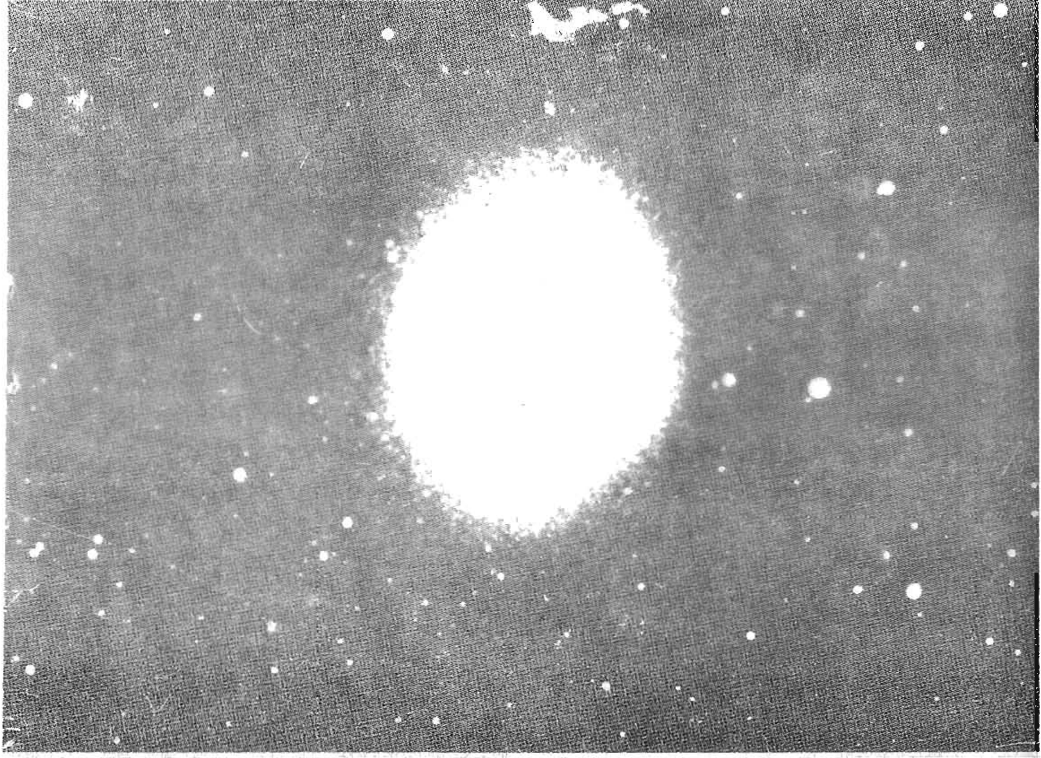
another long-held belief. Our solar system is *not* located at the centre of the Galaxy; rather it is situated two-thirds of the way out, at a distance of about 30,000 L.Y. from the Galactic Centre. Thus, just as Copernicus dethroned the Earth from the 'centre of the Universe' so did astronomers like Harlow Shapley dethrone the Sun from any privileged position in the Galaxy.

So if we want to go to the furthest star in our Galaxy, we have to travel about 80,000 L.Y.—if we wish to go right through the Galactic Centre to the other side.

What will we find when we have crossed the Galaxy?

A spiral galaxy.





An elliptical galaxy.

Here again, another cherished belief has been disproved. Our Galaxy is not at the centre of the Universe. Telescopes show that there are galaxies like ours all over the Universe. Indeed galaxies come in various sizes and shapes, and there is nothing special about our Galaxy. Many galaxies have spiral shapes with two or more arms (containing more densely packed stars) winding out like a spring; quite a few are elliptical, shaped like eggs, while some show no definite pattern or shape.

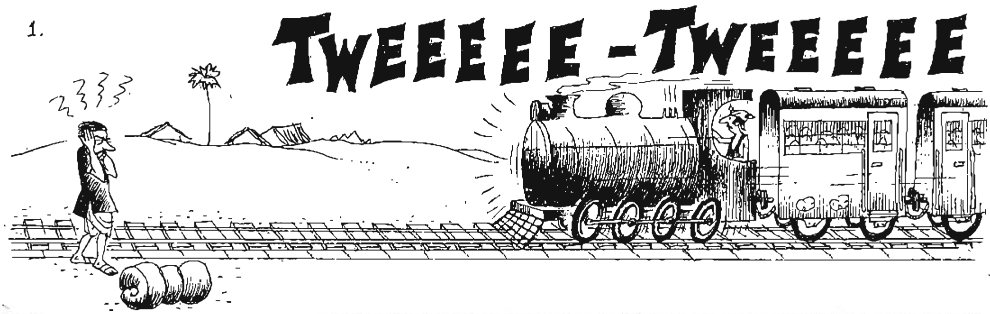
It was in the mid-1920s that we got to know about the rich world of galaxies, thanks largely to improved techniques of observation.

And, by the end of the twenties Edwin Hubble from Mt. Wilson Observatory near Los Angeles made a remarkable discovery. Hubble found that all these galaxies are running away from us! And the farther away a galaxy is the faster does it speed away.

How can an astronomer measure the speed of a remote star or galaxy? He is able to do this because of a property of waves, known as the Doppler effect.

To understand this effect let us take the example of a railway train rushing through a station at great speed. Suppose the engine

1.



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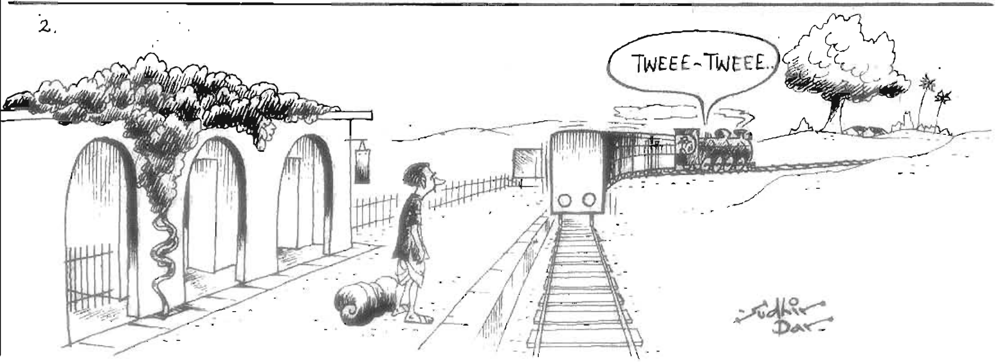
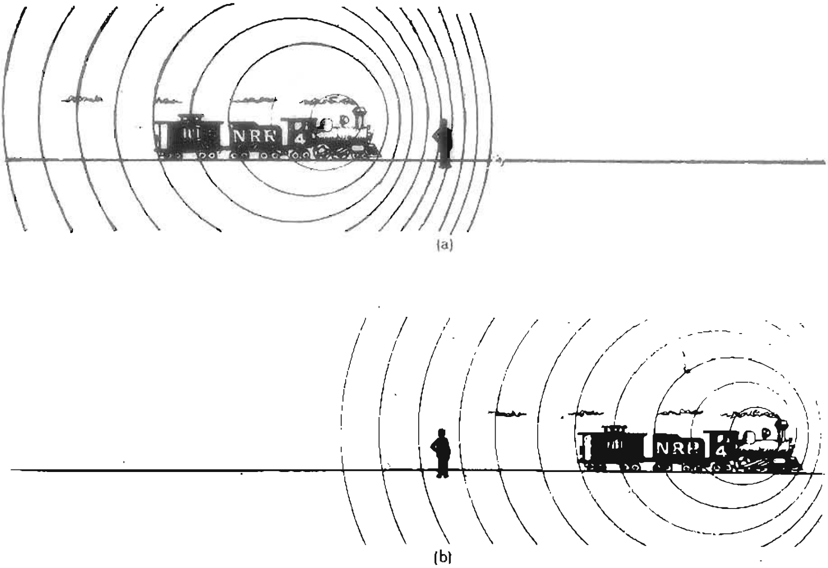




The Doppler effect operates by the decrease of wavelength of sound from an approaching source (the successive waves are closely spaced) and increase of wavelength from a receding source (the waves are spaced apart).

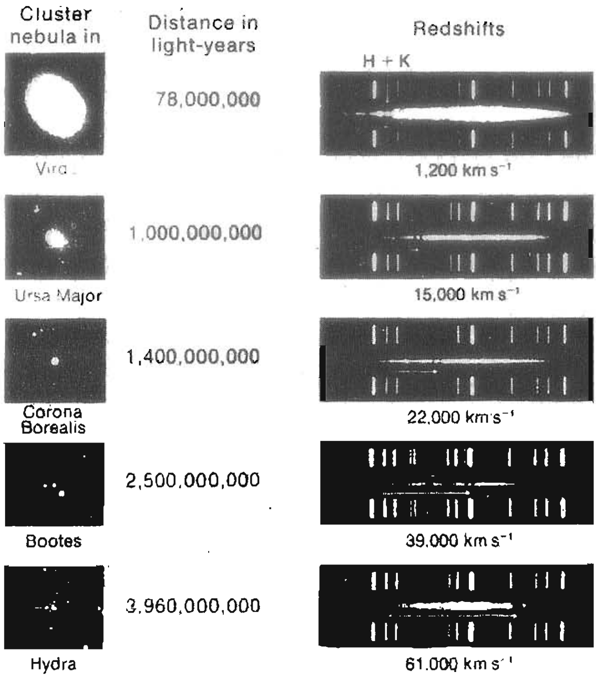
of the train blows its whistle continuously as it dashes past. To a man standing on the platform the whistle sounds very shrill when the engine is coming in and somewhat flat when it moves away. This happens because sound travels in waves, and when these waves are sent out by an approaching source their pitch goes up; when they come from a receding source the pitch goes down.

Applied to light waves, the Doppler effect means that the wavelength of light from a receding source increases. The increase in wavelength is in proportion to the speed with which the source is

moving away. The Doppler effect for light waves is thus useful to the astronomer in finding out whether the source of light is approaching or moving away. In the 1920s Hubble used this effect in the following way:

Just as sunlight splits into several colours when passed through a prism, so does the light from a remote star or a galaxy. The splitting produces a 'spectrum' of the object, telling us how light waves of different wavelengths make up the total light from the source. In addition to the continuous range of colours from red to violet found in the typical spectrum, there are also dark and bright lines. The dark lines indicate absorption of light while the bright ones indicate emission. Atomic theory tells us that the dark lines occur when the light from the source is absorbed en route by cool atoms while the bright lines come from atoms that radiate at high temperatures. From this we now know that individual atoms have characteristic wavelengths at which they either absorb or emit radiation. The specific wavelengths at which the dark or bright lines occur can therefore tell the astronomer the type of atom causing them.

Hubble found dark lines in the spectra of galaxies and by measuring their wavelengths he was able to identify that they were due to the atoms of calcium. However, these lines occurred at wavelengths longer than expected—the lines were *shifted* towards the *red* end of the spectrum. With the help of the Doppler effect Hubble was able to work out the speed of motion away from us, of each galaxy he observed. He found that the phenomenon of *red shift* (as it is called) is universal and that the extent of shift is greater for fainter galaxies. Assuming that the fainter the galaxy the more distant it is, Hubble concluded that the farther a galaxy is the faster does it recede from us.



Red-shifts are expressed as velocities, $c\, d\lambda/\lambda$. Arrows indicate shift for calcium lines H and K. One light-year equals about 9.5 trillion kilometers, or 9.5×10^{12} kilometers.
Distances are based on an expansion rate of 50 km/sec per million parsecs.

Photographs of galaxies and their spectra with the H and K absorption lines of calcium. The lines are more red-shifted for fainter galaxies and hence Hubble concluded that fainter galaxies, being farther, recede faster than the nearer brighter ones.

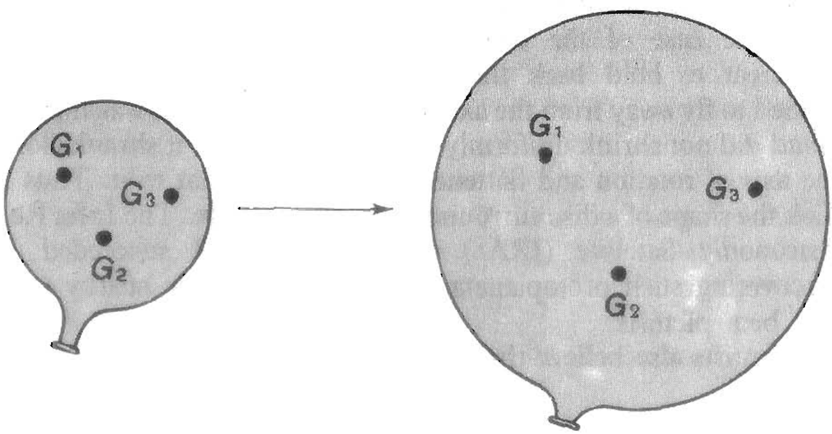
Known as Hubble's law, this conclusion dramatically changed our view of the Universe. It led to the idea that the Universe is 'expanding'; the galaxies are moving away from one another much like the dots on a balloon that is inflated. And, of course, there is nothing special about our Galaxy. If we were to look at the Universe from another galaxy, we would notice the same thing: other galaxies would be seen moving away from our new vantage point.

How far does this expansion extend? With our present telescopes, the answer is "as far as we can see", which is up to distances of several billion L.Y. Thus, when an astronomer photographs a galaxy one billion L.Y. away, he is seeing it as it was one billion years ago. It is quite likely, that by now the galaxy may not be there at all!

So if we venture out of our Galaxy the chances are that we will meet more and more galaxies as we travel on for billions of light years. So far there is no evidence that there is a limit to the Universe. The limit is rather on what we can see and how much we can understand.

Let us examine how far we have succeeded in unravelling the mysteries of the Universe. We begin with our own environment—the solar system.

The expansion of the Universe can be compared to the expanding surface of a balloon that is being inflated. The dots G_1, G_2, G_3 move away from one another as the balloon expands.



Origin of the Solar System

How was our solar system created? A complete answer is not yet known. Current findings suggest the following picture:

It is believed that the Sun, the planets, their satellites and other smaller components of the solar system were formed from a cloud of gas. Initially the cloud was very large and cold. But before long its different components began to attract each other because of the force of gravitation and the cloud thus began to shrink. (It is believed that there was also another event which may have been responsible for triggering off this contraction. We will look at this event later.)

Normally a contracting ball of gas shrinks in size from all directions. However, with the pre-solar cloud, another factor had to be taken into consideration. The cloud was revolving around an axis. This revolution brought into play a further force—the 'centrifugal force'.

If you tie a small stone to a string and whirl it round, the stone tends to fly away from the axis of rotation. This tendency to fly away is caused by the centrifugal force. The stone is held back due to the tension in the string which counters the centrifugal force.

In the case of the contracting cloud, the gravity was not sufficient to hold back the gaseous material, which therefore tended to fly away from the axis of rotation. The result was that the cloud did not shrink uniformly from all directions: it shrank along the axis of rotation and flattened out perpendicular to it. Thus it took the shape of a disc surrounding a central bulge. The Infra Red Astronomy Satellite (IRAS) launched in 1983 succeeded in discovering such protoplanetary discs around a few nearby stars like beta pictoris.

Scientists also believe that magnetic effects played an important

role during the contraction. They slowed down the rotation of the central bulge and increased it on the outer parts of the disc. These effects also led to the disc spreading out much farther than it would otherwise have done.

Well, the central bulge shrank further to form a star that we call the Sun while the disc broke up into lumps that became planets.

Should the string tied to the stone break, the stone will move outwards. This tendency is described by the centrifugal force

The central bulge became considerably hotter than the disc, because when gas is compressed it heats up.

The chemical composition of the planets depended largely on how far they were from the central ball of fire. Imagine various gases moving out from a central region which is very hot. As they moved outwards they cooled. Those which solidified at high temperatures became the nearby planets, while those which retained their gaseous form at low temperatures became the more distant planets. The Earth being one of the nearby planets, therefore has a predominant share of metals while more distant planets like Jupiter or Saturn are made up largely of helium, hydrogen, etc.

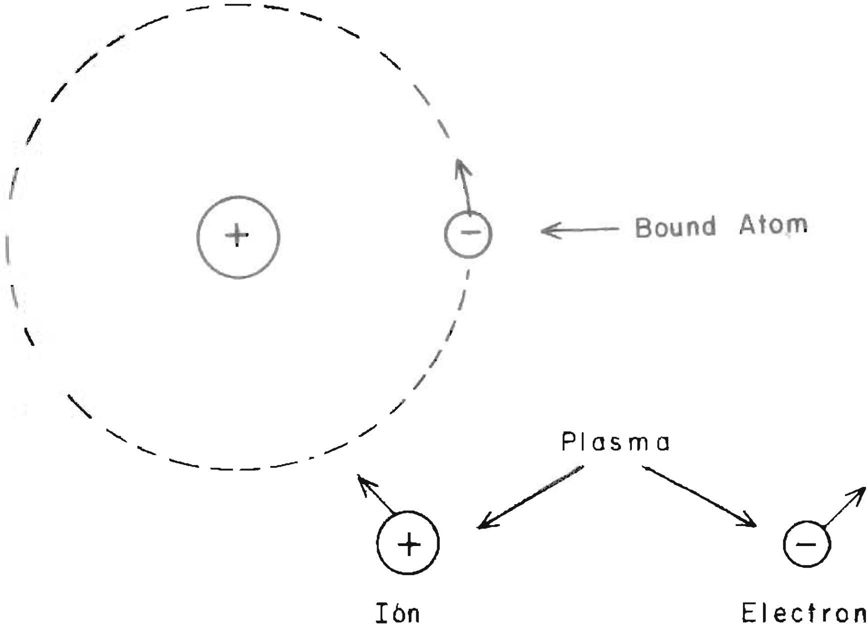
By measuring the fraction of radioactive elements in rocks on the Earth as well as in meteorites (tiny pieces of matter moving round in the solar system) scientists estimate that the age of the solar system is around 4,600 million years.

Was the Moon an off-shoot of the Earth or did it form independently? The samples of lunar soil taken during the many expeditions to the Moon suggest that the Moon's make-up is very different from that of the Earth. So it is likely that the two formed independently and that the Moon somehow got trapped by the Earth's gravitational pull and became its satellite.

The Different Types of Stars

Paradoxically, scientists seem to know more about the stars which are far away than about the planets of our own solar system. There are two reasons for this.

First, the stars (like our Sun) are very hot. At high temperatures of several thousand degrees, matter can exist only in very simple form for at these temperatures atoms, which are the basic building



In a bound atom of hydrogen the negatively charged electron moves round the positively charged proton. In a high temperature plasma the two opposite charges are no longer bound.

blocks of matter, cannot retain their structure. They get stripped of their electrons which move freely. What is left are 'ions' which also move freely. The stars are therefore made of positively charged ions and negatively charged electrons forming a mixture, the 'plasma'. A study of the plasma at high temperatures is easier than that of more complicated atoms and molecules in solid or liquid form at low temperatures.

The second reason why the study of stars is simpler is that there are so many of them. How this helps the astronomer can be understood with this imaginary example:

Suppose an intelligent being from outer space visits the Earth and wants to find out about human beings. There are two ways it could do this. One is to go to a maternity hospital, see a child being born and then observe its life in detail. This way our visitor will know only about one human being and that too after watching him or her for several decades. This is time-consuming and not very accurate, for, studying one human being will not give a correct picture of the variety of the human population on this planet.

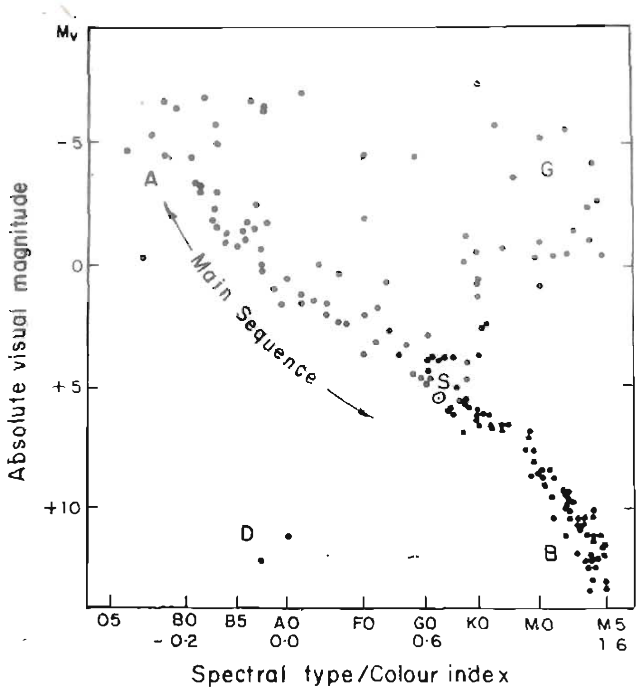
The second method is to survey a group of human beings—say the population of a town. This will provide information about men and women of different ages, their heights, weights and other physical characteristics. Such a study gives an idea of how human beings are born, grow up, get old and die.

In the same way by studying the different types of stars in a group the astronomer can form a fairly accurate picture of how stars are born, how they change with time and how they die. This is a better method, and certainly more effective than looking at only one star. For this, the astronomer needs to know the physical characteristics of stars; how big are they? How hot is their surface? What are the chemical elements on their surface? What are their masses?

Due to the many observational techniques available today and to our greater understanding of the basic laws of science, we now know the answers to these questions. And, of course, just as human beings are not all alike, stars in a cluster exhibit variety.

Two astronomers, E. Hertzsprung and H.N. Russell, devised a good way of classifying stars in a diagram. This diagram is called the H-R diagram, after its inventors. The diagram plots a graph in which the horizontal (x) axis shows the temperature of the surface of the star while the vertical (y) axis indicates the total quantity of energy coming from the star per second.

The Sun's surface temperature is about 5500° Celsius while its luminosity (quantity of light emitted per second) is two hundred million million million megawatts. In the H-R diagram it is the convention to plot the stars cooler than the Sun to its right and those hotter to its left. When such a plot is made for stars in a cluster the following pattern usually emerges: a band of points stretches from the top left hand corner (hot and bright stars) to the



A typical H-R diagram. The Sun's position is shown by S. The absolute magnitude and spectral type/colour index indicate the star's luminosity and surface temperature respectively.

bottom right hand corner (cool and faint stars). This band is called the 'main sequence'. As we shall see, a star spends most of its life on the main sequence. There are some stars outside the main sequence on the top right hand corner. These are bright but cool and are called 'red giants'. Red, because their surface has a reddish tinge: giant, because they are much larger than a main sequence star like the Sun. Similarly, there are a few 'white dwarfs' below the main sequence.

The H-R diagram has been very useful in putting together the biography of a star. We will now see how a star changes its appearance as it grows old and thereby moves its position on this diagram.

The Biography of a Star

Let's look at the life of a star from the time of its birth from a dark cloud of gas. Astronomers have found several dark clouds made predominantly of hydrogen in our Galaxy, in some of which the process of star formation is still going on. How does a star form?

We already know the answer in the case of the Sun. Just as the Sun was formed from a shrinking cloud of gas, so a typical star condenses from a contracting cloud. In fact, the process of star formation may not be confined to only one star at a time. Imagine instead, a gigantic cloud containing enough matter to form a thousand stars, shrinking under its force of gravity. The large cloud cannot retain a coherent shape throughout this process and at some stage it begins to break up into smaller bits. These sub-units are small enough to retain their identity and eventually condense into stars.

When exactly is a star born? A clue to the answer lies in the most visible property of a star: its shine. As in the case of the Sun, the shrinking ball of gas begins to heat up and eventually becomes hot enough to shine. From studying the physical details of star formation we know that in its early stages the star radiates more heat in infrared waves. Indeed, the detection of such waves in the Orion Nebula confirmed that new stars are still being born there.

However, there is more to a star than just its shine. The star must be able to generate enough energy to keep shining. It is the

The Orion Nebula is a region where new stars are believed to have come into existence recently.

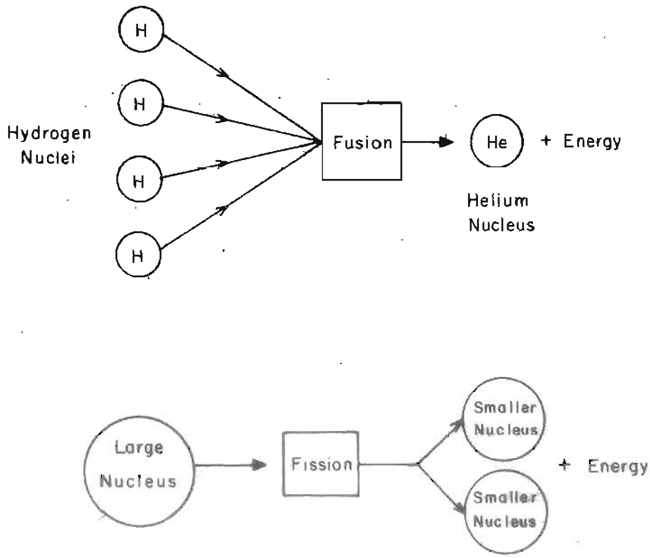
same with the Sun, which is also a star. Man has always wondered where it gets the energy for its radiation.

This question was finally answered about 50 to 60 years ago. The Cambridge astrophysicist A.S. Eddington studied the internal structure of a star and concluded that though the outside temperature of a star is about a few thousand degrees, its central temperature is considerably higher—going up to several *million* degrees! In the 1920s, when Eddington made this startling

discovery the subject of subatomic physics was very new. People knew that in an atom electrons go round a central nucleus. But no one had thought of the possibility of a large nucleus breaking into smaller nuclei or small nuclei joining together to form a big nucleus. Today we know that the former process, known as 'nuclear fission' is the principle behind the atomic bomb, while the latter process of 'nuclear fusion' gives us hydrogen bombs.

Eddington believed that it is the latter process of fusion that goes on inside the Sun. Four nuclei of hydrogen combine to form a bigger nucleus of helium. In this process energy is released, just as in a hydrogen bomb.

There is an important difference, however, between the Sun and the hydrogen bomb. In the hydrogen bomb energy comes out in

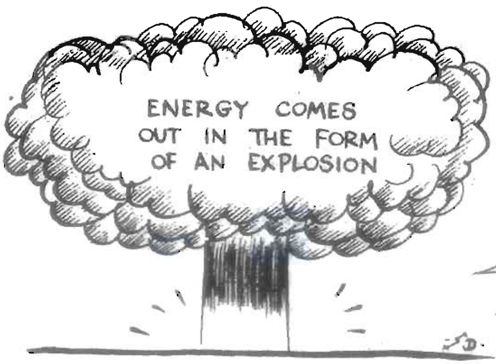


Schematic diagram illustrating nuclear fission and fusion.

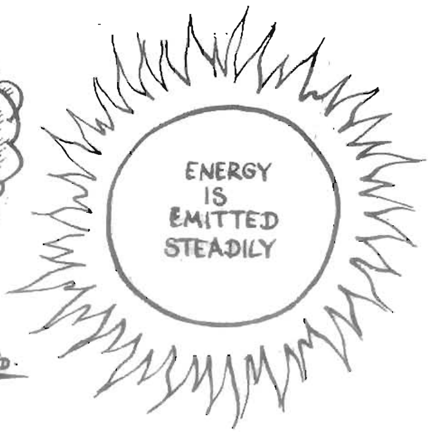
the form of an explosion. Fortunately for human existence on earth, energy is not released in the Sun in a gigantic explosion but is being emitted steadily. This is because the Sun's enormous mass has a strong gravitational force which exercises a restraining influence on the process.

In order to find a lasting solution to today's energy problems scientists are trying to generate fusion energy which is steady and non-explosive. But without the Sun's advantage of a strong gravitational controlling influence other forces and methods have to be discovered. This has not been possible so far, but with the improvement in technology in a decade or two man should be able to succeed in this venture.

To return to the star. The process of converting hydrogen to helium is slow and steady and can supply a star like the Sun with



HYDROGEN BOMB



THE SUN

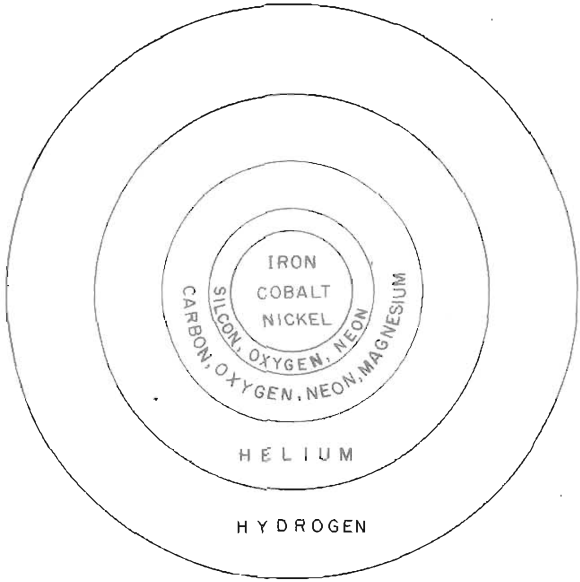
enough energy to last for several billion years. When stars are burning hydrogen in this way and shining steadily, they are on the main sequence of the H-R diagram.

But a stage will come in the life of a star when it exhausts the available hydrogen in its central hot region. What will happen then?

The fusion process in the star is temporarily switched off. When the generation of energy stops the star does not have enough pressure inside and its central core begins to shrink under its own gravity. (The central high pressures are essential for maintaining a star's equilibrium, for a star's natural tendency is to contract under its own gravity. The pressures are able to stop this contraction if they are strong enough.)

The weakening of its central pressure and the shrinkage of its core, however, help restart the star's fusion process. For, as the core containing helium contracts, it heats up. When temperatures rise to about a hundred million degrees, the helium begins to undergo nuclear fusion. Three nuclei of helium combine to produce one nucleus of carbon. In this process more heat is released and this in turn provides enough pressures to hold the star in equilibrium. In fact, the pressures begin to assert themselves so much that the star, instead of contracting, begins to expand. This is when it becomes a giant star.

The Sun will also go through this process after it has exhausted its central fuel of hydrogen. It will then become so inflated that it will swallow the closer planets Venus and Mercury and also gobble up the Earth! But there is no need to get worried; for this will not occur for at least 6 billion years or so. By then, space technologists will undoubtedly have found the means to escape from the Earth alive.



The onion-skin structure of a highly evolved star.

During the giant stage the nuclear process in the star goes through several 'on'-'off' states. When most of its helium is exhausted, the process is temporarily switched off. As before, switching off leads to a shrinking of the central core which then heats up. With it heating up, the process starts again, adding helium to carbon and making the heavier nucleus of oxygen. And thus the process goes on and on, with heavier and heavier elements forming in the centre.

At this stage the star's structure is rather like that of an onion with several skins made of different elements one on top of the other. The outermost and coolest layer is of hydrogen. The next is of helium, followed by carbon, oxygen, neon and so on. The innermost part is made of heavy metals like iron, cobalt and nickel, all formed by successive fusion processes.

The star, however, cannot maintain an unbroken shape after this. Just as an overweight man faces the prospect of heart disease, high blood pressure and other medical complications, so does a massive star have in store a catastrophic future.

The future of stars which are not more than five or six times as massive as the Sun, is quite peaceful. These stars lose their outer envelope in mild explosions or flares and eventually settle down with only the material in the core. The material blown out often appears as an illuminated ring surrounding the star, and is called a 'planetary nebula'. A star exhibiting minor explosions or flares at the surface is called a 'nova star'.

The core that is finally left is very hot but as a star it does not radiate much energy in the visible range. Such a star is called a white dwarf on the H-R diagram. With a density one million times that of water, a handful of material from a white dwarf would contain several tons of matter.

The white dwarf is a strange kind of star. Unlike other stars it does not have thermonuclear reactors producing energy at its centre. How then does it manage to support itself against its own contracting force of gravity? The key to this question lies in quantum theory—the subject that tells us how physical systems behave when studied on the microscopic scale of atoms and molecules. Quantum theory tells us that in the tightly packed material inside a white dwarf a new kind of pressure is built up which resists further compression. This pressure is available, however, provided the star is not too massive.

In the 1930s it was S. Chandrasekhar who demonstrated that for a star to exist as a white dwarf its mass should not exceed approximately 1.44 times the mass of the Sun. If, after the red giant stage is over, the core is left with a mass higher than this limit, the star will continue to shrink. This mass limit is called the 'Chandrasekhar limit' and for this important work Chandrasekhar received the Nobel Prize for physics in 1983.

To complete our discussion of a star's life let us look at the fate of massive stars—those more than five to six times the mass of the Sun called 'supernova stars'. These stars are not able to maintain their internal equilibrium after the giant stage and simply explode.

In a supernova explosion, the star loses its outer envelope in one go. The explosion is accompanied by the ejection of the atomic nuclei of the various elements in the 'onion skin', together with particles called *neutrinos* which are the first to come out.

During the explosion the supernova is extremely bright and can outshine an entire galaxy of a hundred billion stars! This brightness lasts only a few hours, the more long term impact being from the ejected particles and the 'shockwaves' that the explosion generates.

S. Chandrasekhar

In 1054 Chinese and Japanese astronomers recorded sighting a supernova explosion. In the early stages the star was so bright that

it was visible during the day. Now it is not visible to the naked eye even at night. But photographs show a spectacular picture of the debris of the explosion. The star is now named the *Crab Nebula*. In 1987 a supernova went off in the nearby Magellanic clouds. It was not only well documented by optical astronomers but it was also detected by a few neutrino laboratories who recorded the early arrival of neutrinos.

The Crab Nebula is located about six thousand light years away. Had it exploded nearby, say within 30 light years from us, its particles, travelling with great force, would have ripped through the Earth's atmosphere, destroying the layer of ozone gas that protects us from the deadly ultraviolet rays of the Sun.

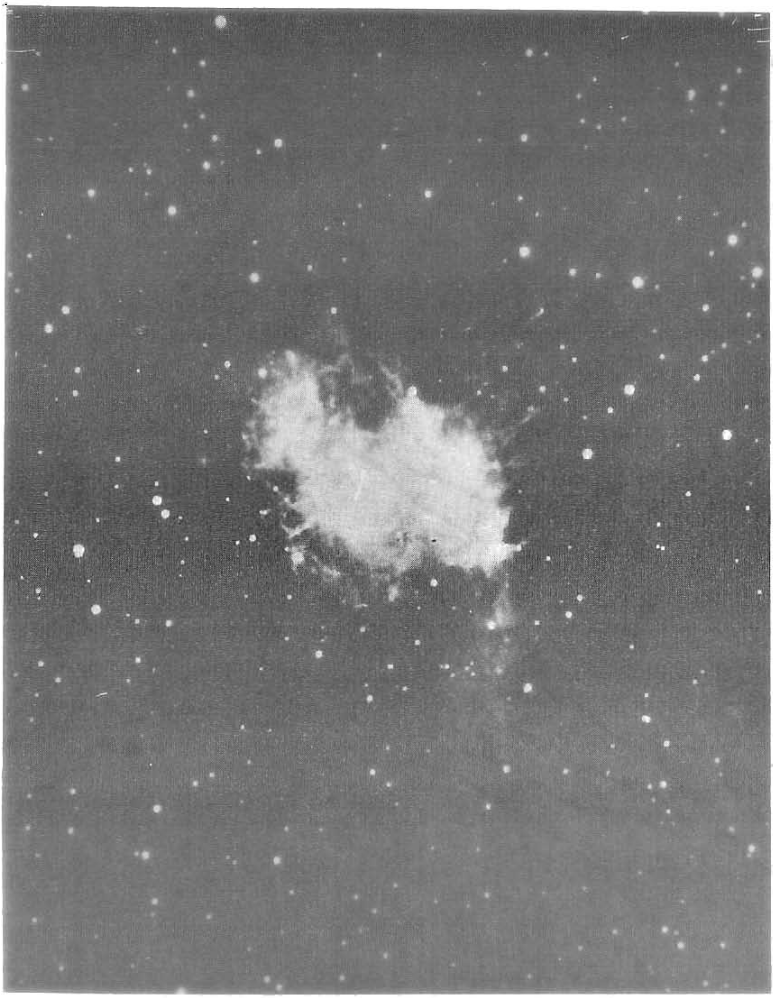
Catastrophic though such an explosion would be for us now, scientists believe that our solar system may have been formed as a result of a nearby supernova explosion. When describing the formation of the solar system, this was the 'another event' that triggered off the contraction of the presolar cloud of gas, for a supernova explosion releases shock waves which, impinging on a nearby gas cloud, can set off its contraction.

Thus the death of one star in an explosion can stimulate the birth of another!

Aftermath of a Star Explosion

When a massive star becomes a supernova and explodes it breaks into two parts: the inner core and the outer envelope. The ejected envelope holds the key to an important and practical question: where do the various chemical elements we see around us, come from?

For example, take a stainless steel spoon. Where did the steel come from? From an iron and steel plant where iron ore was



The Crab Nebula.

subjected to chemical treatment. But where did the iron ore come from? From a mine somewhere in the Earth. How did the iron ore get there? It must have been part of the existing material when the Earth formed. Tracing back the history of the spoon we are finally led to the ultimate source—the supernova.

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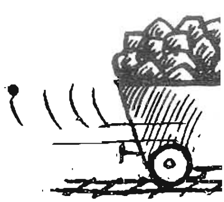

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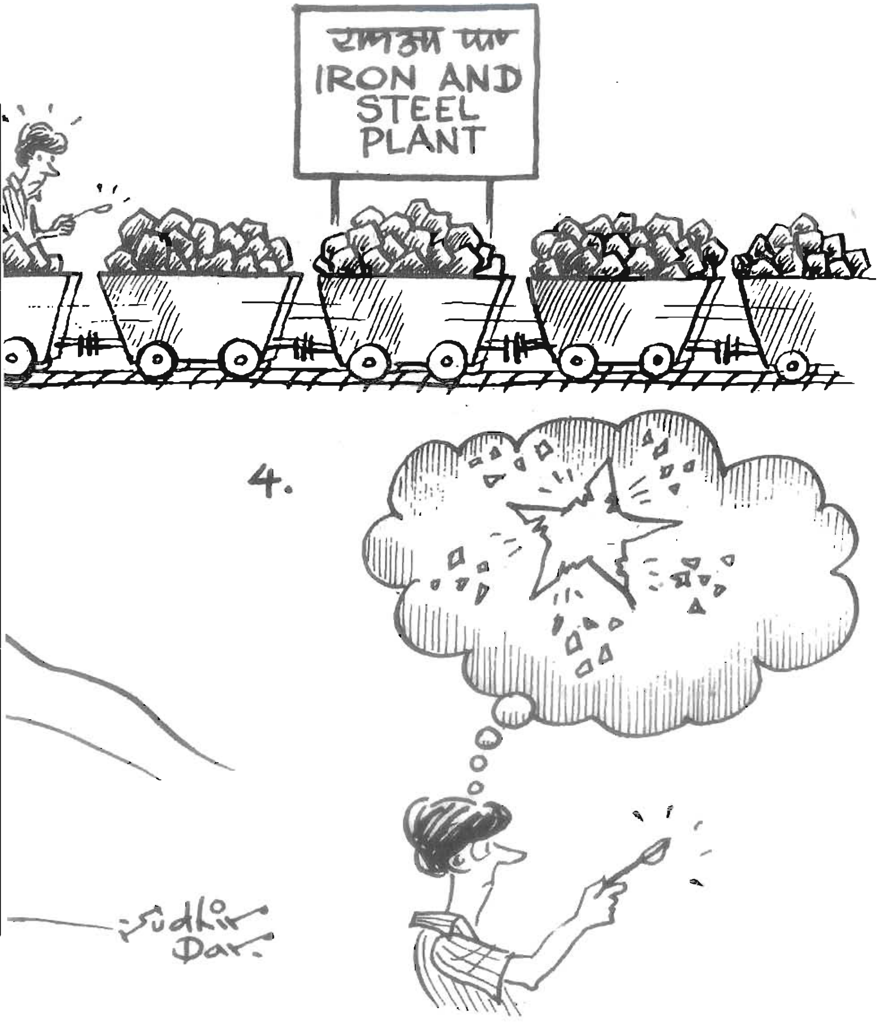
For, at the time of its explosion the star had already manufactured atomic nuclei ranging from helium to iron. So your stainless steel spoon was made from a material which was processed deep inside some star and finally ejected into outer space in a supernova explosion. It has been through a nuclear furnace several billion



degrees hot! Elements heavier than iron are also made inside stars under special conditions.

Four astrophysicists, Geoffrey and Margaret Burbidge, William Fowler and Fred Hoyle have done detailed calculations and found out how the different chemical elements are cooked within the stellar furnace. Later we will come across another method of cooking light elements like deuterium and helium; for it appears that stars by themselves are not able to deliver all of the helium observed in the Universe.

Let's get back to the core left behind after the star's explosion. In the early 1960s it became clear to astronomers that the core by itself remains as a very compact, very dense star, called the 'neutron star'. As its name implies, the star is made up mostly of particles called neutrons. The neutron star is far denser than the white dwarf. The density in its central region is a million billion times the density of water! A neutron star with as much mass as the Sun may not be more than 10-15 kilometres in diameter.

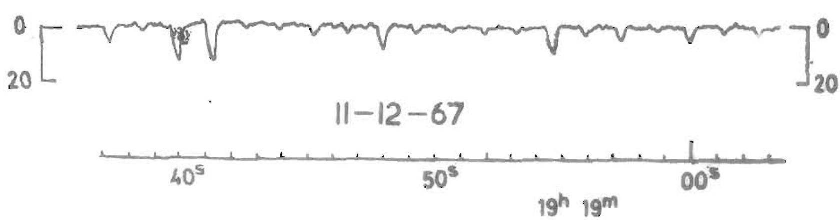
But just as Chandrasekhar found that a star cannot exist as a white dwarf if it is too massive, so do the astrophysicists today find that a star cannot exist as a neutron star if its mass is more than two to three times that of the Sun. So if, for example, a supernova explosion leaves behind a core five times the solar mass, this core cannot maintain itself as a neutron star. Its strong gravitational pull inwards will make it shrink more and more. Before we address our attention to such massive cores, let us ask the more practical question: "If a neutron star is so small in size how do we observe it?"

An accidental discovery in 1968 provided the answer. Jocelyn Bell, a student of radioastronomy at Cambridge University found in the course of some routine observations that faint but regular

pulses from an unknown source were arriving through her telescope. The pulses came at about 1.3 seconds intervals but were repeated so precisely that Bell and her mentor A. Hewish first thought that they might be messages from some distant civilization! Closer examination, however, showed that the signals were in fact coming from a neutron star that was rapidly spinning about an axis. Because of the regularity of the pulses it came to be called a 'pulsar'. Thus a neutron star may not be 'seen' by an optical telescope but can be detected as a pulsar by a radio telescope. The Crab Nebula is also known to house a pulsar which is the remaining core of the supernova of that nebula.

Black Holes

But what about supernova cores that are very massive? According to our present understanding of physics, cores which are so massive that they cannot maintain themselves as neutron stars, continue to shrink until they become mere points. But before they come to this stage, they become what are known as 'black holes'. To understand what a black hole is, let us digress a little.



The pulse pattern of a pulsar.

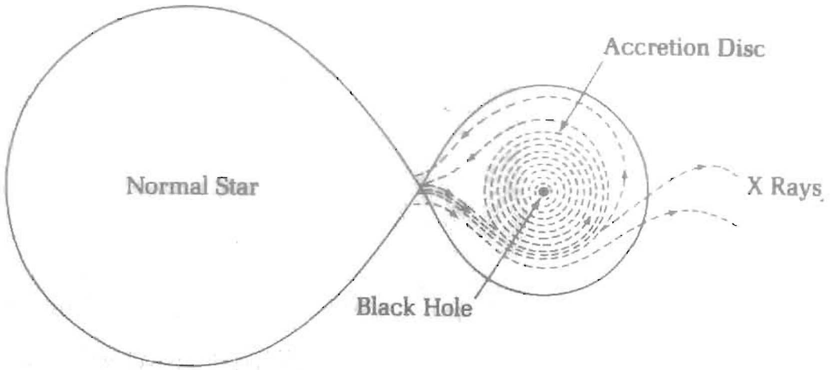
You must have noticed that the harder you throw a ball up in the air the higher it goes; but pulled by the gravity of the Earth it eventually comes down to the ground. Is it possible to toss the ball up so fast that it never comes down? The answer is, "Yes". The limiting speed is about 11.2 kilometres per second. Unless you throw the ball faster than this speed it will come down. This speed is called the 'escape speed'.

Although even the strongest man on Earth does not have enough strength to throw a ball up with the escape speed, we have now made powerful rockets which do. These rockets send up spacecraft that do not have to come down. In 1972, the spacecraft Pioneer 10 was sent up. By now it has not only left the Earth but even the solar system.

Of course, the escape speed depends on the strength of the gravitational pull of the Earth. The Moon's gravitational pull is less than the Earth's and therefore the escape speed too is less, in fact a quarter of that of the Earth. If the Earth was compressed from all sides, its gravitational pull would increase and it would be increasingly difficult to make rockets which could send spacecraft away from the Earth. This is true of any contracting object—as it shrinks the speed needed to escape from it increases.

To get back to the shrinking core. A piece of matter when trying to escape from the core surface will find it increasingly difficult to do so. In fact, a stage will come during the contraction when the escape speed becomes equal to the speed of light. Beyond this stage even light will not be able to escape from the surface let alone any living or non-living object. The shrinking core is then able to pull back all light trying to escape outwards and so it will not be visible to an outside observer.

At this stage it becomes a black hole. A shrinking core with five

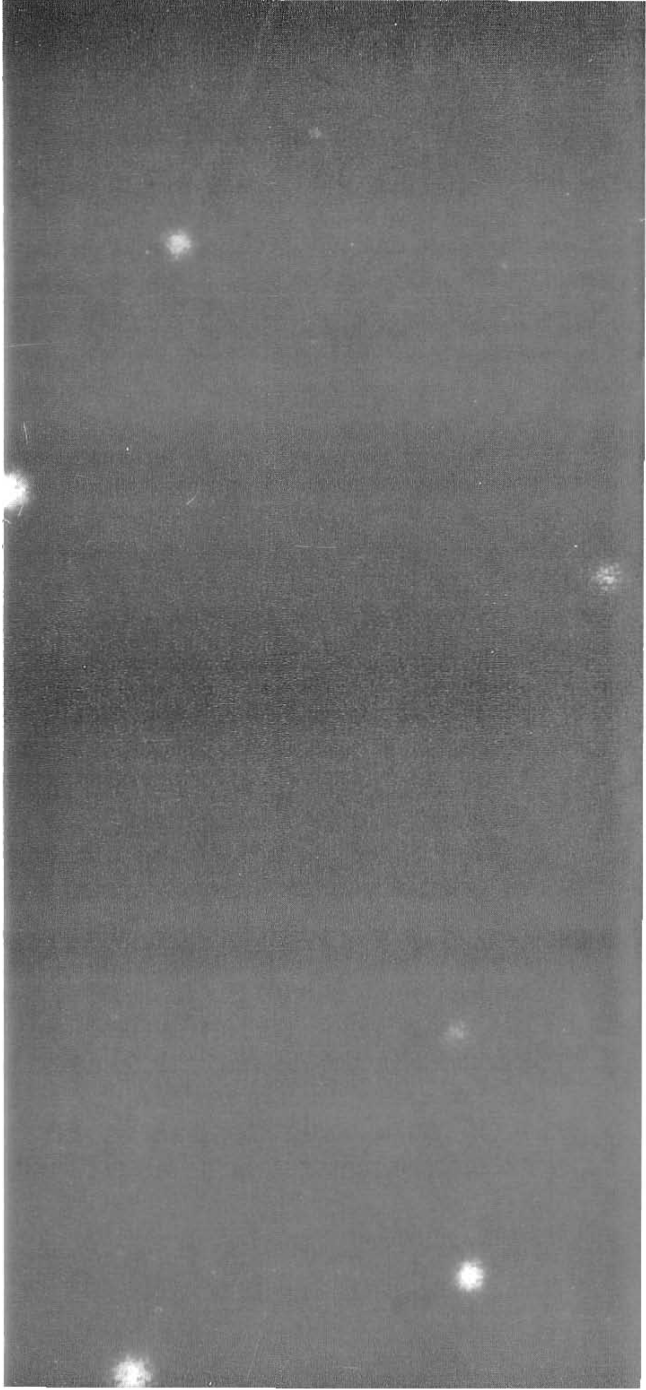


Artist's impression of a double star system containing a black hole. Many believe such a system exists at the location of the X-ray source Cygnus X-1. Figure shows that the matter falling into the black hole forms a disc round it, called the 'accretion disc'.

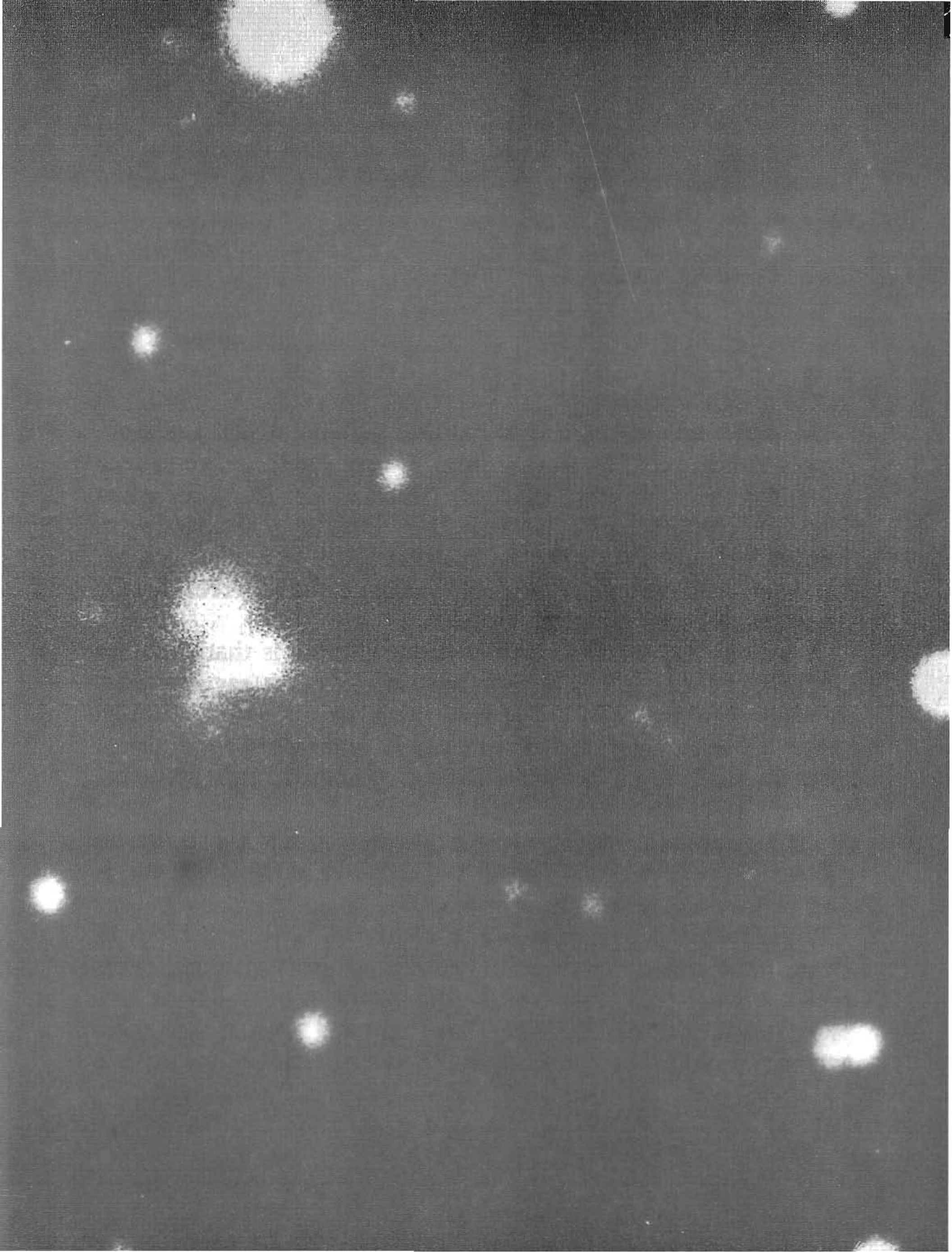
times the mass of the Sun will become a black hole when its diameter is only 30 kilometres.

How do we 'see' a black hole if it cannot emit any light? We can in principle, detect its existence by examining its environment. For, invisible though it is, the black hole continues to attract other matter from its surroundings. A black hole revolving around another star can pull gas from its surface. When falling into the black hole this gas gets heated and radiates X-rays. Many astronomers believe that the X-rays coming from a double star system called the Cygnus X-1 are being emitted this way.

Of course, once the limit of three times the solar mass is exceeded imagination is the limit of a black hole's mass! In Cygnus



Photographs of galaxies and their spectra with the H and K absorption lines of calcium. The lines are more red-shifted for fainter galaxies and hence Hubble concluded that fainter galaxies, being farther, recede faster than the nearer brighter ones.



X-1 the suspected black hole has at least six times the mass of the Sun and black holes much more massive than this are believed to exist in the Universe.

The World of Galaxies

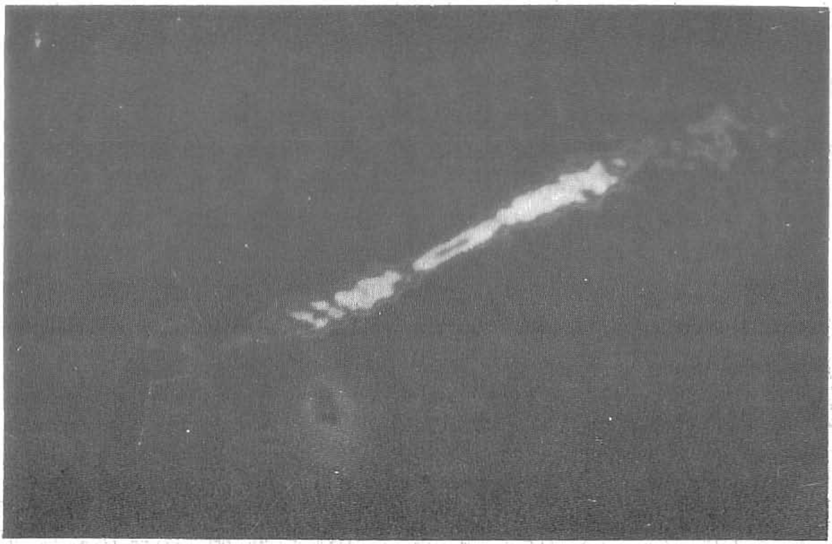
Over the last five decades astronomers have found out how stars are born, how they generate energy and how they manufacture chemical elements in their cores but they are not yet certain how galaxies were formed.

A galaxy has many many stars. Our Galaxy, which has more than a hundred billion stars is neither very small nor very large when compared to other galaxies. Galaxies, like stars, are often found in clusters and it is likely that clusters of galaxies were formed from gas clouds just as clusters of stars were also formed. However, we have not yet been able to explain the different shapes, masses and composition of galaxies.

A curious and puzzling feature about galaxies is that, whether singly or in clusters, they seem to contain a lot more (say, ten times more) unseen matter in and around them than is visible through stars, gas and dust. This dark matter is most probably different from the stuff we are familiar with, e.g. atoms, neutrons, protons, etc.

Radio astronomers have found galaxies which are powerful radiators of radio waves. Cygnus-A, discovered in the late 1940s, is one of the strongest radio sources.

A typical radio source is like a dumb-bell with two blobs of strong radio emission located on two sides of a galaxy. Often there is also a small core that emits radio waves in-between the two blobs. Sophisticated telescopes have revealed jet-like structures emerging from the core towards the outer blobs. Scientists are now



Computer reconstruction of a jet in a radio source.

convinced that plasma at fast speeds is ejected from the central core in jet-like fashion and somehow starts radiating after it collides with the tenuous intergalactic gas in the neighbourhood of the galaxy.

Then in 1963 'quasi-stellar objects'—also called 'quasars' were discovered. As the name implies, these objects look like stars but they are much more powerful. The first quasar to be discovered, 3C-273 may be more powerful than our Galaxy, as far as light emission is concerned. A small percentage of quasars are radio sources also and have a double structure like the typical radio source.

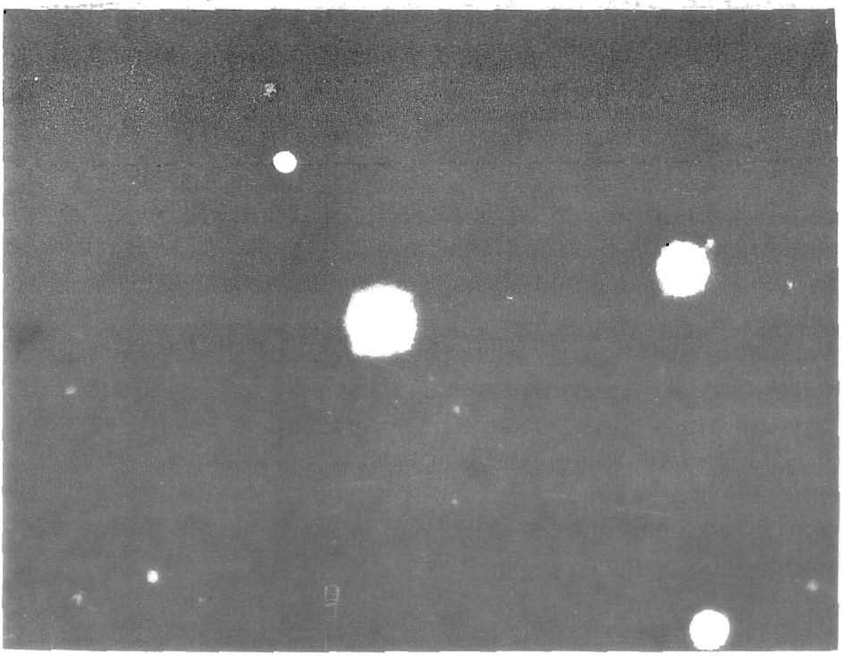
Most astronomers believe that quasars are very far away. Since even from great distances they appear so bright, they must be powerful radiators of energy.

What is the source of the quasar's energy?

Quasars radiate at a powerful rate but unlike the Sun and other stars they radiate from such a small region of space that nuclear energy is not able to account for their extraordinary brightness.

Most astronomers believe that the clue to the quasar's energy lies in gravity. Fred Hoyle and William Fowler in 1963 were of the opinion that a very massive object shrinking under its own gravity

The quasar 3C-273.



could somehow act as a source of the quasar's energy. Today, the same idea is associated with the black hole. A massive black hole, a hundred million times the mass of the Sun, is needed to power a quasar like the 3C-273. But even here, the demands on the efficiency of the energy source are very great and we do not know whether nature permits processes working with such high efficiency.

How did the Universe Begin?

Difficulties of finding answers have never deterred man from asking deep questions. We do not yet know how galaxies and quasars were created. But we have hopes that science will eventually provide the answer. . . So what about the ultimate question: "How and when was the Universe created?"

Hubble's law states that the Universe, as seen at present is expanding. The galaxies in it are moving away from each other. Can we use this information to piece together a historical account of what the Universe was like in the past and to predict what it will be like in the future?

We can, using Einstein's general theory of relativity, determine the history and fate of the Universe and the following picture emerges:

Some ten billion years ago there was a gigantic explosion, often called 'the big bang', which heralded the origin of the Universe. The Universe was extremely hot at the time of creation and had zero volume! But it started expanding and cooling. In its early moments it was dominated by radiation and gradually subatomic particles began to appear in it. What we normally identify with matter began to appear when the Universe was a few billion-billion-billion-billion part of a second old and, when the Universe

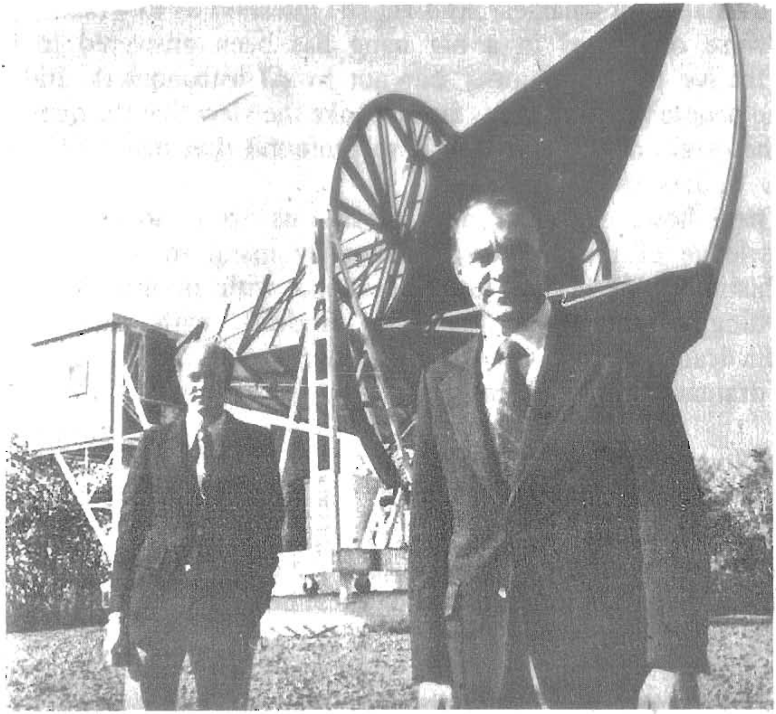
was less than three minutes old, the nuclei of helium, deuterium and other light elements were formed from these subatomic particles. The Universe during this early hot phase was much more efficient than stars in producing helium. It could not, however, produce heavier chemical elements like carbon, oxygen, etc. These elements had to be made in stars.

As the Universe got older and cooler, galaxies began to form in it, but we don't yet know how. Today the Universe is about ten billion years old, and we do not know how long it will keep on expanding and getting cooler. Einstein's theory holds out two possible alternatives. The first is that the Universe will expand for ever while the other is that the Universe will slow down and come to a halt and then contract until it merges back into a point (—sometimes called the 'big crunch'). Neither of these two alternatives need cause us any immediate concern since they will happen billions of years later!

Do we have any direct evidence that the Universe originated in a big bang? No; but we have circumstantial evidence. Indeed George Gamow had predicted in 1950 that if the Universe has cooled down from an early hot state, we should then see some radiation that is the relic of the hot beginning. Of course, the radiation is expected to be very cold today.

In 1965 Arno Penzias and Robert Wilson did find evidence for such an all-pervading cool radiation. This radiation is mainly in microwaves and has a temperature of about 3 degrees on the absolute scale. (The absolute zero of temperature is equal to -273° on the Celsius scale. So we can say that the present temperature of the Universe is -270° Celsius!) Penzias and Wilson received the 1978 Nobel Prize for this discovery.

While the majority of astronomers accept this 'relic' interpreta-



Penzias and Wilson in front of their microwave antenna that led to the discovery of the all-pervading microwave radiation.

tion of the radiation, there are still some outstanding difficulties with this scenario. For example, it is a mystery that the microwave background is found to be so smooth. If it is a relic of the early epochs why does it not carry clear imprints of the events that led to

the formation of galaxies? And so, the question as to whether the Universe originated in a big bang has been answered in the affirmative by the majority but not by *all* astronomers. Indeed some people (including this author) take the view that the question of the origin of the Universe is so profound that man will never fully understand its solution.

That, however, need not prevent us from advancing our knowledge of the Universe further by using more and more sophisticated observing techniques and with improved understanding of the laws of physics. Indeed, with many more sophisticated telescopes in the offing, our view of the Universe is in for dramatic improvement.

The Journey's End

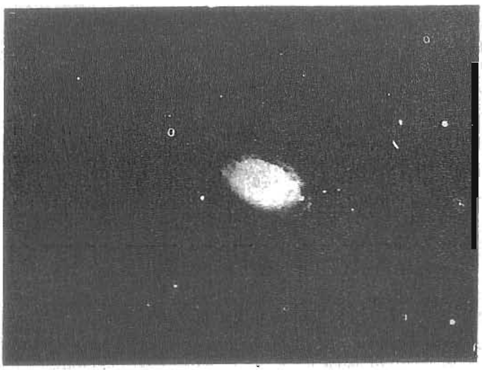
Our celestial journey has taken us from the planets in our immediate vicinity to vast cosmic energy sources billions of light years away. With the help of science man has been able to solve many of the mysteries surrounding these heavenly bodies although much still remains to be explored.

In our tour of the cosmos we saw several things such as, how and why the planets move round the Sun, the sequence of forms a star goes through in the course of its life, how the chemical elements we see around us are manufactured in the cosmos. We also caught a glimpse of the vast world of galaxies that lies beyond the Milky Way, the fantastic concentration of energy in objects like quasars, the systematic way in which the Universe is expanding, and so on.

With the aid of careful observation theoretical astronomers have come up with such interesting concepts as the black hole and the big bang. But to the scientist exploring the cosmos the most exciting discovery is the evidence that this vast cosmos appears to

be governed by basic laws of science, some of which he already knows. Why this is so is still a mystery. As Albert Einstein put it, "The most incomprehensible thing about the Universe is that it is comprehensible".

On this note we end our journey of the Universe.



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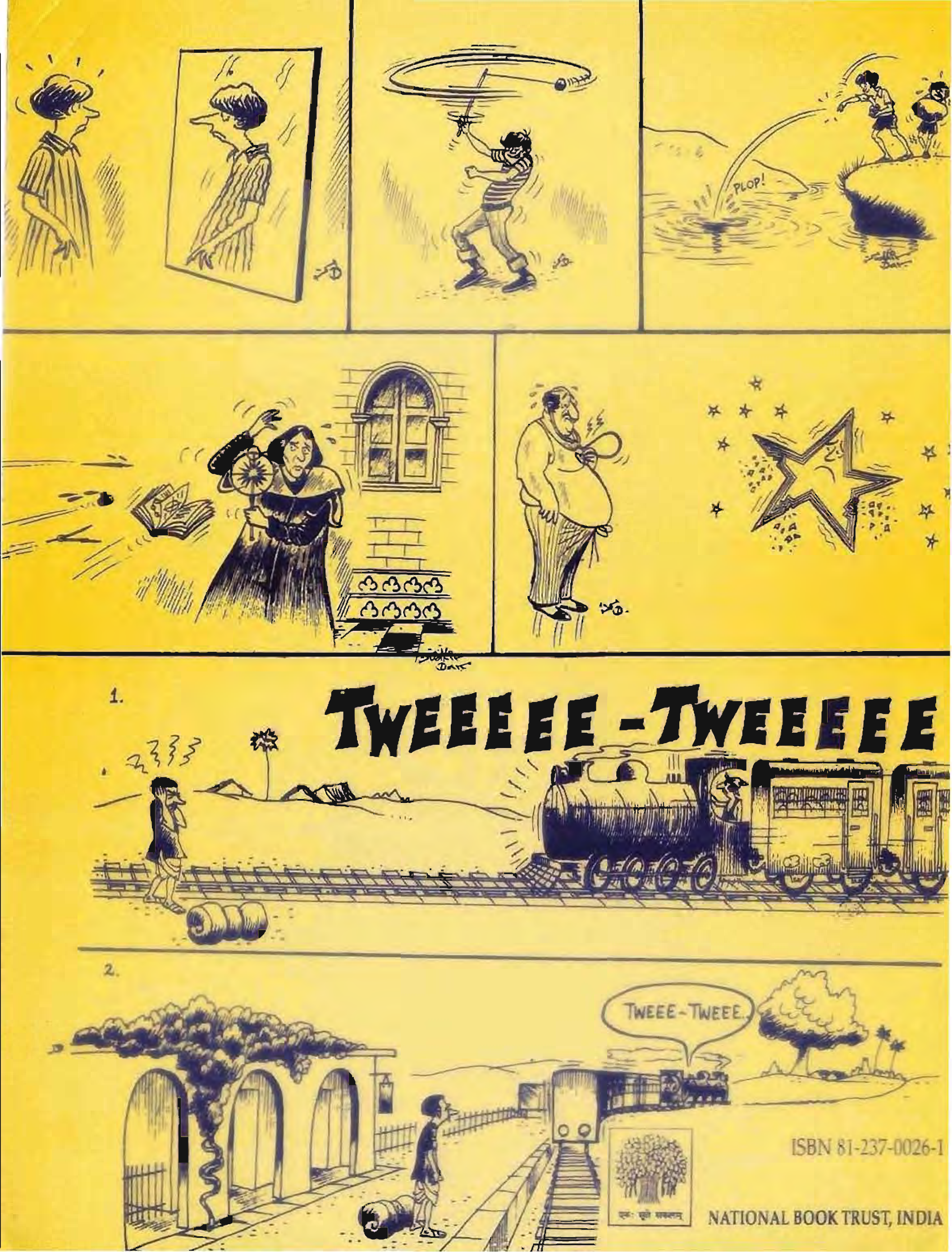

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